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**A HIGH VOLTAGE ELECTRICAL POWER SYSTEM
FOR LOW EARTH ORBIT APPLICATIONS**

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16. ABSTRACT This report discusses the results of testing a high voltage electrical power system (EPS) breadboard using high voltage power processing equipment developed at Marshall Space Flight Center and Ni-Cd batteries. These test results are used to extrapolate to an efficient, reliable, high capacity EPS for near term low Earth orbit, high power applications. EPS efficiencies, figures of merit, and battery reliability with a battery protection and reconditioning circuit are presented.					
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TECHNICAL MEMORANDUM

A HIGH VOLTAGE ELECTRICAL POWER SYSTEM FOR LOW EARTH ORBIT APPLICATIONS

INTRODUCTION

As the pace toward a Manned Space Station accelerates, and as the power and energy demands of other satellites increase, there has been a proliferation of papers on the subject of large space electric power systems (EPS). These have been unanimous in only one area — future space EPS must operate at a significantly higher voltage than the nominal 28 Vdc that has been the workhorse for the first 25 years in space. From there the papers diverge and discuss and/or propose high frequency alternating current (ac) [1,2] electrical power distribution systems (EPDS) at voltages between 200 and 1000 Vac generally at a frequency of 20 kHz, or high voltage direct current (dc) EPS [3,4,5,6] with a distribution voltage between 100 and 300 Vdc.

Data on arcing and plasma interactions have caused concerns about operation of high voltage solar arrays in space, particularly for low Earth orbits where early space stations would operate. This has led to general agreement that the solar array maximum power voltage for a large EPS would be 200 to 300 Vdc maximum. This has little effect on an alternating current EPDS, but the difference between 200 and 300 V could swing the decision of whether a direct current EPDS would be 120 to 180 Vdc or 240 to 270 Vdc. Studies and flight experiments continue to investigate this solar array question.

This paper presents test results and experience for a viable DC EPS that would store energy between 100 and 200 Vdc (depending on power requirements and other system preferences) and provide a regulated or unregulated EPDS as desired. The system breadboard has been in operation for four years and has established a high degree of confidence in the ability to build and operate Ni-Cd batteries and Power Electronics equipment in the range of 100 to 200 Vdc.

HIGH VOLTAGE EPS BREADBOARD

The High Voltage EPS Breadboard block diagram is shown in Figure 1. The primary purposes of this breadboard were to:

- 1) Demonstrate reliable operation of high voltage power processing equipment.
- 2) Demonstrate reliable operation and control of high voltage Ni-Cd batteries (and Ni-H₂ batteries by similarity).
- 3) Provide a test bed for high voltage dc power equipment.
- 4) Generate efficiency data under operational conditions.
- 5) Gain experience with high voltage DC EPS operation.

These purposes have essentially been achieved, and the breadboard continues to operate to enhance knowledge and experience with this technology. Particular emphasis will be placed on purpose 3 as new high voltage equipment becomes available.

Most of the breadboard operation has been with simulated low Earth orbit parameters and in conjunction with a Space Shuttle type bus (28 Vdc) since it is expected that, for some time, there will continue to be some loads — the Shuttle, Spacelab, and Shuttle compatible payloads — that will continue to use 28 Vdc. However, as may be seen in the data presented later, significant gains may be realized by operation with a nominal 110, 140, or 170 Vdc bus.

ENERGY STORAGE

The energy storage in the EPS breadboard has been accomplished with Ni-Cd batteries built with Eagle Picher 60 AH cells connected in 22 cell modules. Four or five modules were then connected in series to provide 88 or 110 cell batteries. These batteries have been cycled at 12 to 15 percent depth of discharge (DOD) during most of the testing. Some early testing was done with a 112 cell, 33 AH battery operating at 25 percent DOD, and with some high rate (100 A) discharge pulses. Recent testing has been done at 40 percent DOD on the 60 AH batteries.

Each battery has a battery protection and reconditioning circuit (BPRC) incorporated to protect against individual cell reversal resulting from either a weak cell during normal operation or a reconditioning [7,8]. The importance of such a circuit, which protects against failures that could propagate into a battery failure, is obvious when one considers the reliability of a large number of cells in series. For a two year cell reliability at 40 percent DOD and 0°C (arbitrarily based on data from Scott and Rusta [9]) of 0.9758, a 110 cell battery reliability of only 0.0678 results. However, even though the individual cell reliability is slightly reduced to 0.9755 by the protection diodes, the useable battery reliability can be greatly enhanced by protecting cells. In a practical system such as shown in Figure 2, several batteries (as required by energy storage requirements) are connected to an unregulated high voltage bus and, through Programmable Transformer Coupled Converters (PTCC), to a low voltage bus. In this configuration a battery with a BPRC can lose up to 10 percent of its cells and still not affect the system operation. Table 1 shows the increase in battery reliability when its usefulness is maintained as cells are lost. With the allowable loss of 10 cells in a 110 cell battery the battery reliability increases to 0.9999 for two years. This ability to protect a battery from cell failure has been demonstrated in the test. The batteries used were built of experimental, non-flight cells which were not accurately matched. As an apparent result, several cell failures (short circuits and loss of capacity) have occurred. Even though some of these failures would definitely have resulted in cell reversal and probable battery failure without a BPRC, no adverse effects have been experienced in the test, and some of the cell anomalies (capacity loss) have been corrected or dramatically improved by a deep reconditioning using the BPRC.

The Ni-Cd batteries in the breadboard have operated at energy efficiencies consistently above 85 percent during investigation of a variety of constant voltage taper current and voltage limit step taper current charge regimes. The major problem encountered has been cell dispersion that apparently resulted from the poor matching and poor charge retention (or high internal leakage) of some of the cells. This has been controlled by occasional reconditioning of the batteries. A reconditioning is accomplished by discharging the battery until all cells are below 0.7 V and

maintaining this level for 40 to 50 hrs. Then the battery is charged for two orbits at rates of approximately rated capacity/10 (C/10) and C/5 A. It is then placed on line at the beginning of a charge period and allowed to recover over a period of several orbits to its fully charged state. The entire process takes about three days with the battery off line for about two days.

The breadboard test has demonstrated that, even with less than ideal cells, Ni-Cd batteries can function reliably in a high voltage configuration. High rate, short duration discharges also showed the ability of the batteries to support very large loads or surges for short periods if necessary.

POWER ELECTRONICS

The chargers and regulators used during early testing were all breadboard programmable power processors (P^3) [6,10] designed and built by MSFC Power Systems Branch personnel. These versatile power processors were programmed to provide the necessary characteristics for a battery charger and a step-down voltage regulator. Recently a programmable transformer coupled converter (PTCC) [11], also designed and built by Power Systems Branch personnel, has been installed to provide the regulator function.

The P^3 chargers have been programmed to provide a variety of battery charging regimes as noted above. The charger P^3 s have been very lightly loaded in testing performed until recently. This simulated a 25 kW power system. Current testing is simulating a 100 kW power system. The light loads resulted in efficiencies of approximately 94 percent, somewhat less than the optimum efficiency of 97 percent for the P^3 in this mode. Further discussion of system efficiency will be presented later. The chargers were programmed to track maximum solar array power in addition to the normal battery voltage-temperature and current relationships required of a charge control device. Solar Array Simulators in the test provided the nonlinear solar array temperature dependent characteristic curve. Maximum power was tracked to within less than 1 percent of actual. However, solar array utilization using Ni-Cd batteries is only 96 to 97 percent as a result of the Ni-Cd trickle charge requirement.

The P^3 regulators, programmed to provide a Space Shuttle compatible 30 Vdc, operated near their maximum power output of 3 kW at this voltage. Although the P^3 has much greater power output capability and is significantly more efficient (97 percent) with a high voltage output, they operated at approximately 90 percent efficiency in this application. They were also programmed to provide for battery sharing, and in conjunction with the BPRC to recondition the batteries and prevent cell reversal or battery overload.

The PTCC was specifically designed for the type application where a voltage reduction of 4 or 5 to 1 is required. As a result it provides higher efficiency and higher power output in addition to dc isolation in the regulator application in the test. Testing at the higher load capability of the PTCC and greater battery depths of discharge, which will also provide more efficient charger operation, is being initiated. The PTCC efficiency is approximately 93 percent in the range of 135 to 200 V input and 30 to 32 V output from half to full load.

TEST RESULTS

As previously noted, the high voltage breadboard has been operating for four years with very positive results. The reliability and efficiency of high voltage Ni-Cd batteries with a BPRC and power electronics have been demonstrated in a variety of modes. The ability to recondition and operate batteries with some degraded and failed cells was demonstrated.

The test bed was primarily designed as part of an EPS for a power module to support and operate in conjunction with the Space Shuttle. This resulted in the configuration of high voltage solar array and energy storage with conversion to low voltage to be compatible with the Space Shuttle — a high voltage/low voltage (HVLV) configuration. This is obviously less efficient than a high voltage solar array/energy storage and high voltage distribution (HVHV) configuration. In addition the topology of the system affects the efficiency. For the test bed EPS the system solar array ratio (R) is defined as follows:

$$R = \frac{P_{sa}}{P_b} = \frac{1}{\eta_O \eta_R \eta_C \eta_I \eta_U} \left(\frac{t_N}{\eta_B t_D} + 1 \right)$$

where

P_{sa} = Solar Array Power

P_b = Bus Power

η_O = efficiency of output distribution system

η_R = regulator efficiency

η_C = charger efficiency

η_I = efficiency of input distribution system

η_U = solar array utilization

η_B = energy storage efficiency

t_N = time of orbit night = 0.6 hr

t_D = time of orbit day = 1.0 hr.

The system efficiency (η_s) is then defined as follows:

$$\eta_s = \frac{t_O}{R t_D}$$

where t_O = the orbit time = 1.6 hr.

For the original test bed with a P^3 regulator and lightly loaded charger the figure of merit is 2.174 and the system efficiency is 73.9 percent. These figures compare favorably with an equivalent low voltage system which would have a solar array ratio and efficiency of approximately 2.25 and 71 percent. However, with optimum charger loading and a PTCC regulator the figures would be 2.056 and 78 percent respectively, a significant improvement. Depending on system requirements, further improvements are possible with different topologies as shown below.

A SPACE STATION ELECTRICAL POWER SYSTEM

Based on the continuing positive results obtained in the MSFC high voltage test bed, it is possible to speculate on a possible EPS for a Space Station. The configuration will obviously depend on the required power levels to a certain extent, but a system similar to that shown in Figure 2 would be able to meet the requirements of loads from 25 kW to 150 kW with minor changes. Tables 2 and 3 show some of the key features, components and variations that might be considered over that load range. Past studies have indicated that, in modular systems, 6 to 24 modules are practical. The lower end is bounded by the percent of a system that is lost when an element fails. For six batteries, failure of one would lead to an increase from 40 to 48 percent DOD which is very near the cost optimized Ni-Cd battery in Reference 12. At the upper end this limit of 24, though somewhat subjective, is based on the increased complexity. With these limits and the option of 50 or 100 AH batteries, Table 2 shows the choices one has if 110 cell and 132 cell (five 22 cell modules or six 22 cell modules) batteries are considered. As an example, consider a 100 kW load requirement using 6 module 100 AH batteries. Nine Ni-Cd batteries weighing approximately 12,600 lb would provide for a 40 percent DOD. Six Ni-H₂ batteries using 150 AH cells would weigh approximately 5,000 lb.

The power electronics would consist of PTCCs as required (approximately 5) and nine P^3 chargers. The PTCCs would provide the low voltage power and array battery sharing and reconditioning required. The P^3 s would charge the batteries, track the solar array maximum power, assist in battery reconditioning as required, and provide the signals to open the charger bypass switches if required. The system solar array ratio and efficiency as a function of amount of low voltage power used are shown in Table 3.

The solar array ratio for supplying power to the high voltage bus of this system is:

$$R = \frac{P_{SA}}{P_B} = \frac{1}{\eta_O \eta_I \eta_U} \left(\frac{t_N}{\eta_B \eta_D \eta_C t_D} + 1 \right) .$$

The ratio for supplying power to the low voltage bus of this system is:

$$R = \frac{P_{SA}}{P_B} = \frac{1}{\eta_O \eta_I \eta_C \eta_R \eta_U} \left(\frac{t_N}{\eta_B t_D} + 1 \right) .$$

The parameters are defined as before for the appropriate buses, etc. As shown in Table 3, the ratio for the system distributing only high voltage is 1.842, i.e., the average solar array power during the sunlight portion of the orbit must be 1.842 times the orbital average bus power. As a comparison, for the same system distributing only low voltage power, the average solar array power would have to be 2.094 times the orbital average bus power, i.e., $R = 2.094$. Somewhat higher solar array utilization (0.98 compared to 0.96) could be realized with a different energy storage system, fuel cell/water electrolysis for instance, but the lower energy storage efficiency (0.65 compared to 0.85) would result in worse ratios. The costs for the additional solar array and drag makeup, weight different, life, development, etc. for the entire mission life will have to be assessed to make the proper energy storage selection. If development time permits, some alternative to the ubiquitous Ni-Cd battery may prove acceptable. A tradeoff is also possible in the charger area where a solar array switching system could replace the P^3 chargers with some improvement in efficiency. However, this will result in decreased solar array utilization since solar array maximum power cannot be tracked with such a system. It is estimated that there will be little if any difference in the solar array ratio, so the tradeoff will be on cost, versatility, etc. for the power electronics.

The system presented, based on technology that has been thoroughly tested, is considered to be a prime candidate for an early Space Station. The major elements would be on-orbit replaceable, the efficiency would be high, and the reliability would be high based on utilization of a modular approach. The system is also compatible with energy storage elements other than Ni-Cd batteries should a viable alternative become available in time for a Space Station.

FUTURE ACTIVITY

The operation of this high voltage breadboard will continue to evaluate new hardware as noted above. In addition MSFC is in the process of building a higher voltage (200 to 300 Vac) breadboard for evaluation of that technology and has plans for an alternating current breadboard to be used as a direct comparison with direct current systems. Implementation of these plans will assure that a thorough comparison of the potential EPS technologies for a Space Station are completely and fairly evaluated, and that the best selection for a Space Station EPS will be made.

TABLE 1. HIGH VOLTAGE BATTERY RELIABILITY

Reliability (R) of 110 cell Ni-Cd battery and BPRC with allowable cell loss of N cells

N	R
0	0.065912
1	0.247396
2	0.494953
3	0.718028
4	0.867391
5	0.946648
6	0.981365
7	0.994276
8	0.998437
9	0.999617
10	0.999915
11	0.999983

TABLE 2. HIGH VOLTAGE EPS-Ni-Cd BATTERY CONSIDERATIONS

	System Power				Units
	25	50	100	150	kW
<u>110 Cell Battery</u>					
Load Voltage	142 ± 22	142 ± 22	142 ± 22	-	V
Average Discharge Voltage	138	138	138	-	V
Average Discharge Current	184	362	725	-	A
Capacity Required - 40% DOD	276	540	1088	-	AH
50 AH Batteries	6	11	22	-	EA
100 AH Batteries	-	8	11	-	EA
<u>132 Cell Battery</u>					
Load Voltage	170 ± 30	170 ± 30	170 ± 30	170 ± 30	V
Average Discharge Voltage	165	165	165	165	V
Average Discharge Current	152	303	606	909	A
Capacity Required - 40% DOD	228	455	909	1364	AH
50 AH Batteries	5	9	19	-	EA
100 AH Batteries	-	5	9	14	EA

TABLE 3. 100 kW HIGH VOLTAGE EPS - LOW VOLTAGE
LOAD CONSIDERATIONS

	31 ± 1 Vdc Power					Units
Power Level	0	5	10	15	20	kW
Number of PTCC Required	0	1	2	3	4	—
Figure of Merit	1.842	1.855	1.867	1.880	1.892	—
System Efficiency	86.9	86.3	85.7	85.1	84.5	%

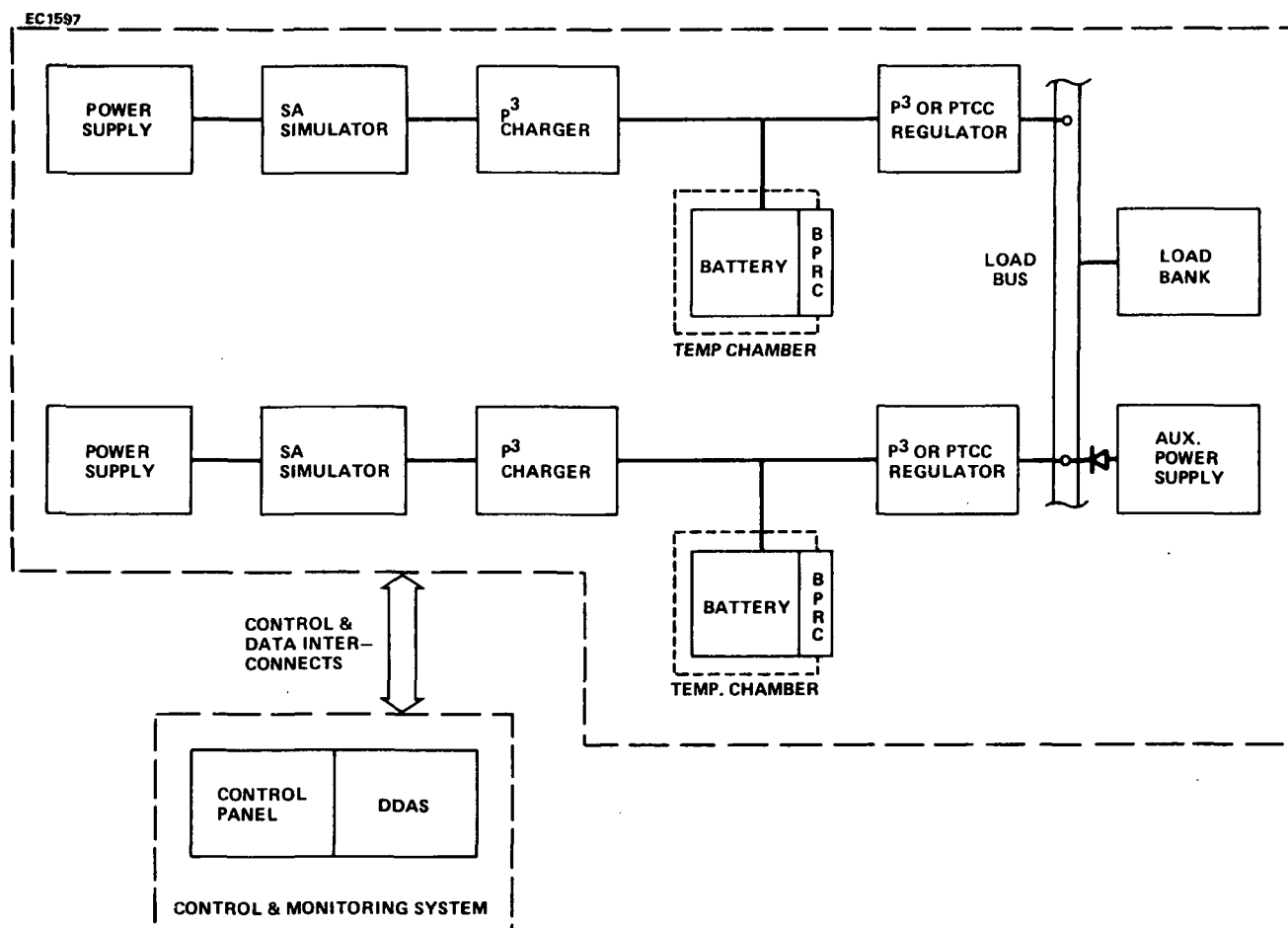


Figure 1. High voltage EPS breadboard.

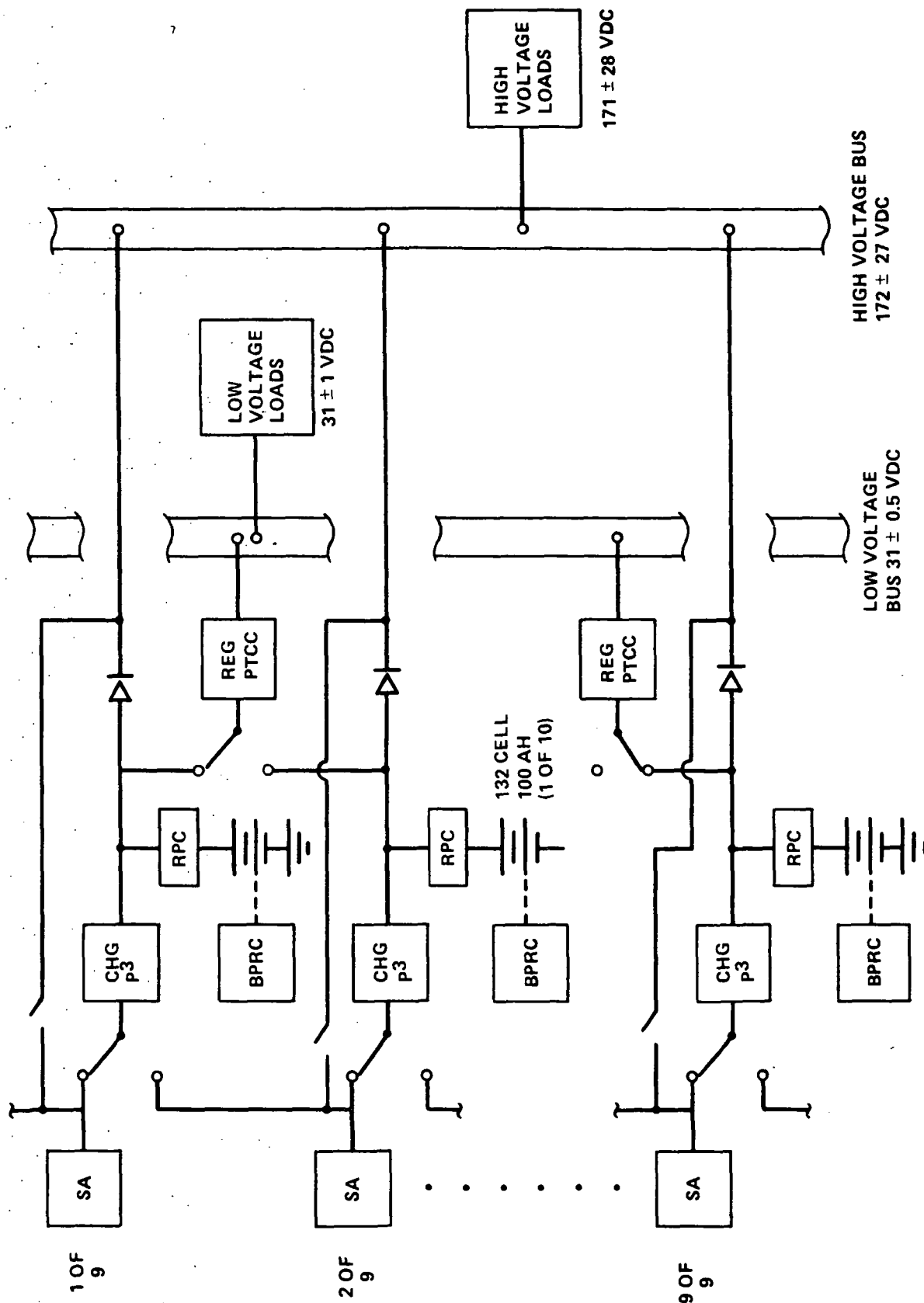


Figure 2. A 100 kW high voltage EPS.

REFERENCES

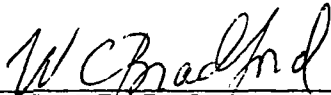
1. Renz, D., et al.: Design Considerations for Large Space Electric Power Systems. NASA Technical Memorandum 83064, April 1983.
2. Mildice, J. W.: Study of Power Management Technology for Orbital Multi-100 KWe Applications, Volume 1. NASA CR 159834, July 15, 1980.
3. Gilmour, A. S., Jr.: Investigation of Power Processing Technology for Spacecraft Applications. AFWAL-TR-82-2054, June 1982.
4. Corbett, R. E., et al.: High Voltage High Power (HVHP) Solar Power System. AFWAL-TR-81-2103.
5. Bush, J. R., Jr. and Kapustka, R. E.: Programmable Power Processor Parametric Test Report. EC12-(129/81), December 16, 1981.
6. Lanier, R., Jr., et al.: A Programmable Power Processor for a 25-kW Power Module. NASA TM 78215, January 1979.
7. Lanier, Roy: A Nickel-Cadmium Battery Reconditioning Circuit. NASA TN D-8508, June 1977.
8. Lanier, J. R., Jr. and Bush, J. R., Jr.: Life Test of a Nickel Cadmium Battery With a Protection/Reconditioning Circuit. NASA Technical Paper 1873, May 1981.
9. Scott, W. R. and Rusta, D. W.: Sealed-Cell Nickel-Cadmium Battery Applications Manual. NASA Reference Publication 1052, December 1979.
10. Lanier, J. R., Jr., et al.: A Programmable Power Processor for High Power Space Applications. Power Electronic Specialists Conference 1982 Record ISSN 0275-9306, June 1982.
11. Kapustka, R. E., et al.: A Programmable Transformer Coupled Converter for High Power Space Applications. Power Electronics Specialists Conference 1984 Record, June 1984.
12. TRW Report Number 345-79-6001-UT-00, Volume 1, Reference EPS Design, Contract NAS 8-33198, April 1982.

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



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